

Suppressed neutrino oscillations and large lepton asymmetries

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ABSTRACT

It is shown that hypothetical neutrino-majoron coupling can suppress neutrino flavor oscillations in the early universe, in contrast to the usual weak interaction case. This reopens a window for a noticeable cosmological lepton asymmetry which is forbidden for the large mixing angle solution in the case of standard interactions of neutrinos.

1. Introduction

Cosmological lepton asymmetry is not directly measurable, in contrast to baryon asymmetry, but may be observed or restricted through its impact on big bang nucleosynthesis (BBN), large scale structure formation, and the angular spectrum of the cosmic microwave background radiation (CMBR), for a review see e.g. Ref. [1]. At the present time the best bounds follow from the consideration of BBN. According to Ref. [2] they are: $|\xi_e| < 0.2$ and $|\xi_{\mu,\tau}| < 2.6$. Therefore the lepton asymmetry can be large, and its origin and implications are discussed by many authors [3].

The bounds on chemical potentials of ν_μ and ν_τ can be significantly improved because of the strong mixing between different neutrino flavors [4]. This mixing gives rise to the fast transformation between ν_e , ν_μ , and ν_τ in the early universe and leads to equilibration of asymmetries of all neutrino species. Thus the BBN bound on any chemical potential becomes essentially that obtained for ν_e [5] (see also the papers [6]):

$$|\xi_{e,\mu,\tau}| < 0.07. \quad (1)$$

In this case the cosmological impact of neutrino degeneracy would be negligible.

It is interesting to see if one could reasonably modify the standard model to allow large muonic and/or tauonic charge asymmetries, together with a small electronic asymmetry, to avoid conflict with BBN. This is the aim of this work. A natural generalization is to introduce an additional interaction of neutrinos with massless or light (pseudo)Nambu-Goldstone boson, majoron [7]. Let us note that in this paper we consider an impact of neutrino majoron interactions on the oscillations between active neutrinos and not on

active-sterile oscillations [8,9].

2. Neutrino-majoron interactions

We assume the following neutrino-majoron interaction:

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \sum_a \bar{\nu}_a \gamma^\mu \partial_\mu \nu_a + \frac{i}{2}\chi \left(g_{ab} \nu_a^T C \nu_b + g_{ab}^* \nu_b^\dagger C \nu_a^* \right), \quad (2)$$

where χ is the majoron field, and ν_a is four-component representation of neutrino of flavor a . Here ν_a is taken to be left-handed. This interaction induces the effective potential for neutrinos with momentum \mathbf{p} [10]:

$$\left[V_{\mathbf{p}}^{(x)} \right]_{ab} = \int \frac{d^3\mathbf{q}}{(2\pi)^3} \frac{1}{4|\mathbf{p}||\mathbf{q}|} \left[g^\dagger \left(\rho_{\mathbf{q}}^T + \bar{\rho}_{\mathbf{q}}^T + f_\chi(\mathbf{q}) \cdot \mathbf{1} \right) g \right]_{ab}, \quad (3)$$

where $\rho_{\mathbf{p}}$ ($\bar{\rho}_{\mathbf{p}}$) is the density matrix for (anti)neutrinos, $f_\chi(\mathbf{p})$ is the number density of majorons with momentum \mathbf{p} , and $\mathbf{1}$ is the unit matrix in the flavor basis.

The weak interaction as well induces the effective potential for neutrinos, $V^{(w)}$, the exact form of which can be found in e.g. Ref. [12]. If $V^{(x)}$ dominates over $V^{(w)}$, the neutrino oscillations can be suppressed. To be precise, the diagonal part of the potential $V_{aa}^{(x)}$ should be larger than the weak potential $V^{(w)}$, while its off-diagonal components must be much smaller than the diagonal ones, that is, the flavor symmetry in the neutrino-majoron interactions should be strongly broken. To this end, we assume that the coupling constant matrix g_{ab} is approximately diagonal and one of the diagonal components dominates over the other components. For a more generic form of g_{ab} , see Ref. [10].

The coupling constants g_{aa} should not be too large, otherwise flavor non-conserving reactions of the type $\nu_e \nu_a \leftrightarrow \bar{\nu}_e \bar{\nu}_a$ (or similar) would lead to equilibration of all leptonic charges. To avoid that the rate of these reactions, $\Gamma_{ea} \sim \sigma_{ea} T^3$, should be smaller than the cosmological expansion rate $H \sim T^2/m_{Pl}$, where $m_{Pl} = 1.221 \cdot 10^{22}$ MeV is the Planck mass. Thus, to suppress $e - \mu$ or $e - \tau$ transformation through direct reactions one needs

$$g_{aa}^2 g_{ee}^2 < 10^{-22} \left(\frac{T}{1 \text{ MeV}} \right). \quad (4)$$

This conditions should be satisfied for temperatures above the BBN range, i.e. $T > 1$ MeV. Similarly, if we require that $\nu_a \nu_a \leftrightarrow \bar{\nu}_a \bar{\nu}_a$ should not occur efficiently, the coupling constants must satisfy a similar inequality with g_{ee} replaced with g_{aa} .

Furthermore, there are quite strong limits on possible coupling of majoron to neutrinos which follow from astrophysics. Astrophysics allows either very small or quite large coupling constants. The former is quite evident, while the latter appears because strongly interacting majorons, though efficiently produced inside a star, cannot propagate out and carry away the energy, thus opening a window for large values of the coupling. It is not so for the coupling to ν_e because the latter is bounded from above by the data on double beta decay, $g_{ee} < 3 \cdot 10^{-5}$. Together with the supernova bounds, the upper limit is shifted down to $g_{ee} < 4 \cdot 10^{-7}$ [11], with a small window around $(2 - 3) \cdot 10^{-5}$. So we assume in

the following that $g_{ee} \ll 10^{-7}$. For μ or τ the allowed regions are: $g_{aa} < (3 - 5) \cdot 10^{-6}$ or $g_{aa} > (3 - 5) \cdot 10^{-5}$. Not to erase the lepton asymmetries, the former allowed region is assumed.

3. Results

Using the effective potential shown in the previous section, we have calculated the evolution of the lepton asymmetries both analytically and numerically. Here we show only the numerical results, and see Ref. [10] for the analytical method. In doing the numerical calculations, we have assumed that the mixing is effective only between two neutrinos since the atmospheric neutrino mass difference is much larger than the solar one. Also the coupling constant matrix g_{ab} is approximated to be $g_{ab} = g \delta_{a\mu'} \delta_{b\mu'}$. The numerical result is shown in Fig. 1, which says that, as $|g|$ increases, the oscillations become less efficient and completely stop for $|g| \gtrsim 10^{-7}$. Note that we have obtained consistent results by the analytic method.

4. Conclusions

In this paper we have shown that the hypothetical neutrino-majoron interaction can suppress neutrino oscillations in the primordial plasma to prevent lepton asymmetries of all neutrino species from being equilibrated. The exact form of the effective potential induced by this interaction is calculated. We have found an allowed range of the coupling constant: $10^{-7} < |g| < 5 \cdot 10^{-6}$, which satisfies the astrophysical bounds and makes the scenario operative. For the coupling constant in this range, $\nu_e - \nu_{\mu'}$ oscillation in the early Universe is blocked, thereby keeping the cosmological lepton asymmetry of electron type unchanged. The upper bound comes from the requirement that lepton number is effectively conserved, and the lower bound is obtained from the study of the evolution of the lepton asymmetries both analytically and numerically, in two flavor approximation. The constant matrix in the simplest class of majoron models can satisfy the desired constraints, in the case of the normal mass hierarchy. Thus we conclude that an addition of the majoron field to the standard model can reopen a possibility that the effect of ξ_e is compensated by large $\xi_{\mu,\tau}$ (or by the extra energy of majoron itself), thereby curing a probable discrepancy between the BBN and CMBR.

5. References

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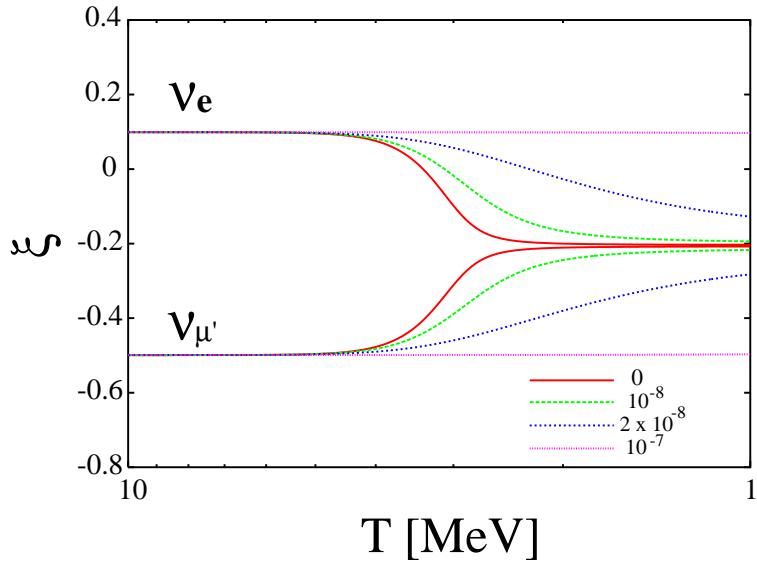


Figure 1: The evolutions of ξ_e and $\xi_{\mu'}$ for several values of $|g|$ with $\sin^2 \theta = 0.315$ and $\delta m_{21}^2 = 7.3 \times 10^{-5} \text{ eV}^2$. The initial conditions are $\xi_e = 0.1$ and $\xi_{\mu'} = -0.5$.

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